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Title: SPACE SOLAR POWER SATELLITE SYSTEMS WITH A SPACE ELEVATOR

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Space Solar Power Satellite Systems with a Space Elevator

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1. Introduction

The Space Elevator (SE) represents a major paradigm shift in mankind's access to outer space. If the SE's promise of low-cost access to space can be realized, the economics of space-based business endeavors becomes much more feasible. In this paper, we describe a Solar Power Satellite (SPS) system and estimate its costs within the context of an SE. We also offer technical as well as financial comparisons between SPS and terrestrial solar photovoltaic technologies.

Even though SPS systems have been designed for over 35 years, technologies pertinent to SPS systems are continually evolving. One of the designs we present includes an evolving technology, optical rectennas.

SPS systems could be a long-term energy source that is clean, technologically feasible, and virtually limitless. Moreover, electrical energy could be distributed inexpensively to remote areas where such power does not currently exist, thereby raising the quality of life of the people living in those areas. The energy "playing field" will be leveled across the world and the resulting economic growth will improve the lot of humankind everywhere.

2. Parameters of the Study

The scenario described in this paper is an SPS system at geosynchronous earth orbit (GEO). Such a system orbits permanently above its ground station, i.e., the station on Earth to which it beams its power. The SPS system contributes 1 gigawatt (GW) to the electrical power grid on Earth. In other words, the solar cell array in orbit generates enough power to overcome all system inefficiencies such that the grid on Earth receives 1 GW.

An SE infrastructure was assumed to exist. Nominally, this is two-200 metric tonne capacity cables and two-20 metric tonne capacity cables. This assumption was done only to ensure the throughput of such a system would not "bottleneck" the SPS logistics. In other words, the time taken for cargo in transport on an SE would not be a limiting factor. Since this technology is still in its first stages of serious study, only estimates of SE launch costs are presented in this analysis.

Electrical power flowing through an SPS system begins with solar flux impinging on the solar cell array in orbit, converting that sunlight directly into electricity. This electrical power is then converted to microwave power by a magnetron and beamed to Earth by a transmitter array. On Earth, a rectenna receives the microwave energy converting it back to direct current (DC) electricity. Finally, a static inverter system converts the DC electricity to alternating current (AC). That AC power then flows onto the power grid.

The solar cell array area is expected to be destroyed by meteor impact or radiation degradation at a rate of 5 percent per year. Thus after 20 years, there is a less than 36 percent probability that any given portion of the array has not been replaced. This also affords new and more efficient technologies to be incorporated in the SPS system in continuously. It is further assumed robotics dominate the construction and maintenance tasks of the SPS system since GEO is an inhospitable place for humans.

A computer model incorporating solar cell technologies and performance, array size and mass began the study. Launch costs, estimated construction schedule and costs, magnetron technology and efficiency, transmission losses, receiver antenna array efficiency, static inverter technology and efficiency, ground[1] and maritime[2] transportation costs, as well as maintenance estimates were included. All these costs were based upon current retail market prices. While we realize the demand of a project of this magnitude could conceivably drive the market price down, this was not included in the analysis as the amount of decrease is intangible at this point.

Another point that needs to be realized about current market costs is that they are based on the current market price of electricity being approximately $0.10/kW-hr. If the price of electricity is increased five or six times the current rate, one would expect the cost of capital items, i.e. the solar arrays, static inverters, magnetrons, etc, would increase as well. An increase in the capital costs would then lead to an increase in amortized annual expense.

The financial analysis considered the cost of amortized capital funds and revenue from electrical generation. Additionally, any net loss of income was assumed to be carried over to the next year's operation, while any Net Positive Income (NPI) was assumed to be expended as dividends and/or retained earnings. In this way, the profitability of the SPS system was determined using metrics such as the time needed to produce a NPI as well as the net present value of such an investment.

A baseline scenario was defined and then varying one parameter and observing its effect on a parameter of interest accomplished subsequent analyses. Thus, the parameter was investigated over the variables of most interest.

3. Baseline Scenario

The baseline scenario uses an array of various solar cells sufficient to generate 1 GW on Earth, launched into space with a launch cost of $100/kg. The array requires three years to construct after which an estimated annual deployment rate of 25 percent would occur. Maintenance and operating costs are not considered at this point because they could be absorbed by simply raising the product's unit price, which starts at $0.12/kW-hr.

Power capacity	1 GW
Launch costs	$100/kg
Construction term	3 years
Deployment rate	25% /year
Selling price	$0.12 / kW-hr
Land costs	$100 / acre
Investment return	10% / year
Investment term	10 years
Loan rate	3%
Loan term	30 years

Table 1. Baseline Scenario Parameters

Land costs for terrestrial operations are assumed to be $100/acre. A comparison we present is the differences between SPS operations and the equivalent terrestrial solar operations. It was initially hypothesized that land costs may be a significant portion of needed capital, but only to the extent of the difference the two operations need. An arbitrary figure, which can be easily changed in the model, was set at $100/acre.

Construction capital is to be amortized at 3 percent over 30 years. Additionally, a 10 percent return on investment over a 10-year period is assumed. **Table 1** summarizes these parameters.

For each of the technologies for collecting solar flux compared in this study, the remaining system must be in place. That is, a magnetron system, a rectenna, and a static inverter with their inefficiencies must exist to complete a useful SPS system. **Table 2** shows the residual components of the SPS system.

Magnetron loss	10%[3]
Magnetron mass, kg	3.36E+05[4]
Magnetron costs	$138,435,513[5]
Atmospheric loss	2%[6]
Rectenna loss	9%[7]
Rectenna cost	$1,831,501,832[8]
Static Inverter loss	10%[9]
Static Inverter costs	$144,444,444[10]

Table 2. Residual components of an SPS

4. Solar Cell Technology Comparison

Many solar cell technologies can be considered for an SPS. The simplest is the thick-film and the most advanced is the optical rectenna. Each of these technologies have its advantages. A new technology, the optical rectenna[11] (OR), is the most efficient and thus requires the smallest array area. The thin-film or flexible photovoltaic (FPV) solar cells have the lowest mass/unit area, but are much less efficient. The final solar cell technology to be considered here is thick-film

Operating Efficiency	86.8%[12]
Total System Efficiency	49.8%
Total area, km^2	1.44E+00
Total mass, kg[13]	3.30E+06
System Costs[14],[15],[16]	$ 2,042,396,521
Total Construction Cost	$4,551,013,644
Years to NPI	6
NPV, $M	$83

Table 3-1. SPS Optical Rectenna Technology

Operating Efficiency	40.0%[17]
Total System Efficiency	16.0%
Total area, km^2	4.49E+00
Total mass, kg[18]	9.54E+06
System Costs[19]	$ 2,732,102,766
Total Construction Cost	$5,904,055,631
Years to NPI	7
NPV, $M	($1,135)

Table 3-2. SPS Thick-Film Photovoltaic Technology

Operating efficiency	25.5%[20]
Total System Efficiency	5.6%
Total area, km^2	1.29E+01
Total mass, kg[21]	1.18E+08
System Costs	$ 5,341,854,312
Total Construction Cost	$20,035,446,985[22]
Years to NPI	33
NPV, $M	($22,086)

Table 3-3. SPS Thin-Film Photovoltaic Technology

photovoltaic (TFPV). While TFPV is less efficient than OR promises to be, it is a known and proven technology. **Table 3-1** through **3-3** summarizes the parameters of the different technologies for a 1GW baseline SPS system.

5. Transportation Costs vs. Profitability

Quintessentially, business transportation costs refer to the cost of shipping the product from the manufacturing plant to the consumer. In the case of an SPS, however, it refers to the cost of shipping the entire manufacturing plant into geosynchronous orbit. In either case, low transportation costs are critical to business, more so for any space-based endeavor.

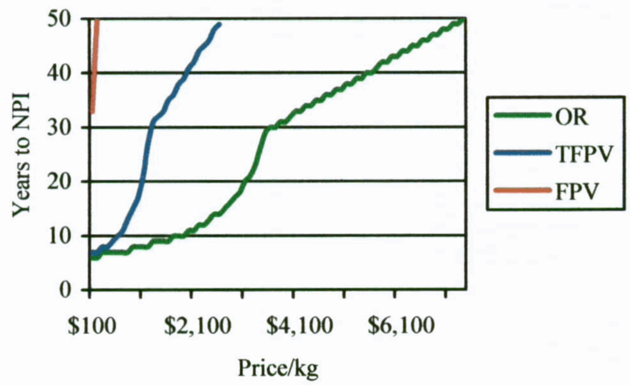

Figure 1. Years to NPI as a Function of Launch Costs.

Figure 1 shows the effect of the increase of transportation cost of an SPS system on the years to show a net positive income. While it is possible to attain a NPI with high transportation costs, it is obviously easier with lower costs. It should be noted the change in the slope of the two curves is due to the effect of the 30-year amortized capital expense.

6. Electricity Cost vs. Profitability/ Net Present Value Analysis

As **Figures 2** shows, the unit price that the product is sold has a pronounced effect on how quickly an SPS system can show a Net Positive Income (NPI). Even with a low product price, SPS systems in our model can eventually achieve an NPI, even though it may take a long time. As the price increases, the limiting factor in achieving an NPI is construction and deployment.

Net Present Value (NPV) is defined as the discounted or present value of all cash inflows and outflows of a project or of an investment at a given discount rate[23]. Simply put, NPV is an indication of how much cash will need to be invested in the present, at a given rate, to achieve future inflows and outflows all summed together. A positive NPV indicates an investment that will at least return the given baseline rate of 10 percent/year over 10 years.

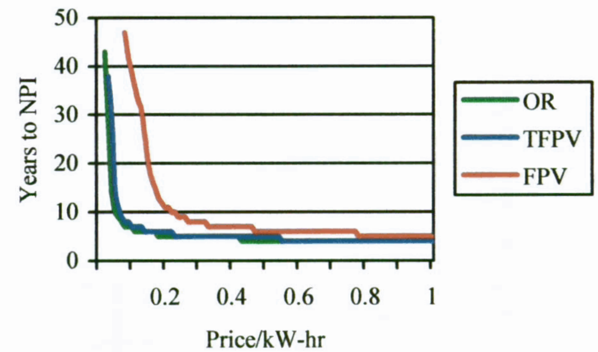

Figure 2. Comparison of Product Price to Years until NPI

As **Figure 3** shows, some OR and TFPV technologies can be a good investment with low product price, while FPV would not be a good investment until product price were four to five times higher.

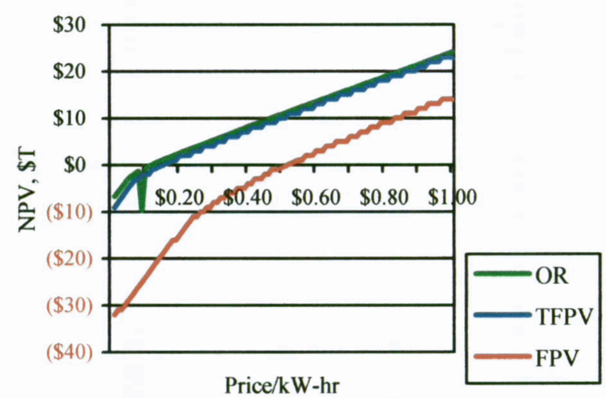

Figure 3. NPV as a Function of Product Price.

It should be noted this analysis is based on the current market price of electricity at approximately $0.10/kW-hr. Hence, the valid range for this analysis would be in the general area of $0.10/kW-hr. A large increase in the market price of electricity, as noted earlier, would reflect an increase in capital costs. This analysis does not include such an increase. That is not to say this analysis in invalid; it can be used to show general trends.

6. Ground-based Solar Array vs. an SPS

Strickland,[24] as well as many others, has presented logistical, environmental, as well as philosophical and moral arguments to indicate the advantage of SPS technology over ground-based solar arrays. While these arguments are no less valid, the overriding factor for the outlay of any business capital is profitability.

Using the same criteria used in the above baseline scenarios, **Tables 4-1** through **4-3** can be developed.

Operating Efficiency	86.8%
Total System Efficiency	81.6%
Total area, km^2	6.61E+00
Total mass, kg	2.04E+07
System Costs	$9,357,402,792
Total Construction Cost	$9,806,330,102
Years to NPI	9
NPV, $M	($496)

Table 4-1. Terrestrial Optical Rectenna Technology

Operating Efficiency	40.0%
Total System Efficiency	37.6%
Total area, km^2	1.44E+01
Total mass, kg	4.43E+07
System Costs	$8,581,432,726
Total Construction Cost	$9,064,048,627
Years to NPI	8
NPV, $M	($459)

Table 4-2. Terrestrial Thick-Film Photovoltaic Technology

Operating Efficiency	25.5%
Total System Efficiency	24.0%
Total area, km^2	2.25E+01
Total mass, kg	2.73E+07
System Costs	$9,296,692,808
Total Construction Cost	$9,755,600,392
Years to NPI	9
NPV, $M	($494)

Table 4-3. Terrestrial Thin-film Photovoltaic Technology

By comparing the respective terrestrial technologies to their SPS counterparts, it can be seen that terrestrial technologies are at a disadvantage in size, cost, years to NPI, and NPV. The prevailing reason for this is the lack of solar flux (about 7.5 times less) that a same-sized solar panel array on the surface of the Earth receives compared to what is possible in outer space.[25]

7. Conventional Power Generating Plants vs. an SPS

Construction costs for conventional power plant generation are currently determined to be much lower than our analysis shows. **Table 5** shows comparative costs. Only recently has decommissioning costs been factored into power plant costs.

Technology	Construct cost, $/kW
Nuclear[26]	1,400
Coal[27]	1,500
Natural Gas[28]	1,281
Hydro[29]	240
Wind[30],[31]	3,030
Terrestrial OR	10,005
Terrestrial TFPV	9,322
Terrestrial FPV	9,756
SPS OR	4,551
SPS TFPV	5,935
SPS FPV	20,035

Table 5. Comparative Construction Costs

A 1990 Pace University report entitled "Environmental Costs of Electricity" estimated nuclear power costs 10 to 15 cents per kilowatt hour, compared to 6 to 8.3 cents for coal, 4 to 6 cents for natural gas, 5 to 12 cents for wind, and 8 to 20 cents for solar, fuel costs, especially for natural gas, are likely to have changed since then. With environmental costs factored in—including costs of accidents and decommissioning—nuclear power jumps from 12.9 to 17.9 cents per kilowatt-hour, the study found.[32]

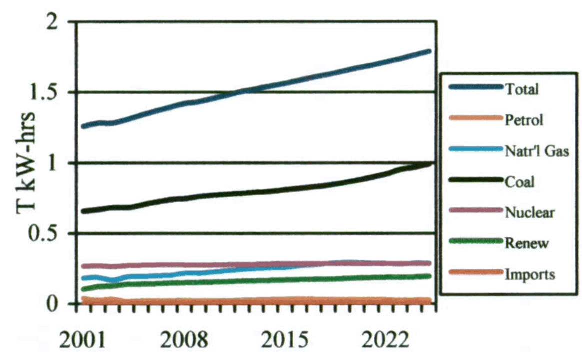

Figure 4. Projected Electricity consumption in the US.

According to the US Energy Information Administration (EIA),[33] predicted electricity generation would rely heavily on coal-fired power plants. It can be seen from **Figure 4** the United States will be relying more and more upon coal-fired power plants for future electrical energy.

Energy and environment are closely linked, and there are clear signs our current reliance on fossil fuels may lead to instabilities with significant social, environmental, economic and political consequences in the future. This year alone, coal-fired power plants will introduce 6,000 million metric tonnes of carbon-dioxide, 10.2 million metric tonnes of sulfur-dioxide, and 3.3 million metric tonnes of nitric-oxide[34] into the atmosphere.

8. SPS Benefits

In a pure economic argument where only supply and demand matter, logic indicates that fossil fuel will eventually be depleted and at a progressively higher rate of cost per unit. Technologies of clean alternative energy sources of sufficient capacity are still in their infancy.

The viability of SPS technology is partially demonstrated by the many satellites already powered by solar cells. Other aspects of the system, such as wireless power transmission, appear within the grasp of current technology. The keystone to making an SPS system profitable is low launch costs. Currently, only the SE promises those low launch costs.

The promise of SPS's inexpensive power and very minimal impact on the environment combine to make this SPS technology one of the most desirable power sources for the future.

9. Conclusions

Initially, we felt that land costs were going to be a significant portion of the capital needed for such a project, and hence was included in the financial analysis. However, with a project of this magnitude, land costs became a small percentage of the estimated costs until the costs approached \$10,000/acre.

While they have utility in applications of confined payloads or mass per unit area, low system efficiency technology, such as thin-film photovoltaics probably would not be a good candidate for a profit motive production facility, such as an SPS.

Recently, an article appeared in Spacedaily.com which indicated the cost for a proposed SPS system would yield a product cost of about \$0.21/kW-hr.[35] Our analysis shows a product price of approximately half that. The fundamental difference between these two studies is launch costs.

The study in the Spacedaily article was done by Japan's Ministry of Economy, Trade and Industry (METI), in which conventional chemical rockets were used to launch their SPS. Utilizing the model developed in this study, if the launch costs are increased from the baseline \$100/kg to \$700/kg, then construction costs are approximately equal.

In a pure business sense, where the bottom line is paramount, any company whose product costs are almost double that their competition's for the same product will lose. The only difference between these two analyses is the mode of transportation.

As Leonard David reported on Space.com, "... for any SSP program to churn out commercially competitive terrestrial electric power, breakthrough technologies are required."[36] Only the SE promises to be that breakthrough technology.

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